AGRICULTURAL MEMORANDUM NO. 526

RESTRICTED CIRCULATION

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CRITICAL TEMPERATURES OF YOUNG BEEF CATTLE

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1. INTRODUCTION

The environmental temperature below which an animal has to increase its heat output in order to prevent its body temperature from falling is called its Critical Temperature. If additional food is not made available, the increase in heat output can only come from the catabolism of body reserves (essentially fat); there is then an evident association between the occurrence of environmental temperatures below the Critical Temperature and the economics of animal production (where this is measured primarily in terms of body weight gain).

The concept of a Critical Temperature subsumes that of a constant body temperature maintained by an energy balance. It involves both the thermal environment (through the environmental demand) and the level of feeding (through the heat increment due to feed).

Most determinations of Critical Temperatures will have been made on individual animals by calorimetric studies, where the obvious step is to identify environmental temperatures with the ambient air temperature (after noting that the radiative temperature of the calorimeter surfaces will be close to that of the air). Also, most determinations of Critical Temperature will have been made under nominally still air (free convective) conditions. The interest in this memorandum lies in the determination of Critical Temperatures in the farm environment, where wind effects (and forced convective air flows) must be considered and where the radiative temperature of the animals surroundings can no longer be equated with the air temperature. The preferred first approximation to an environmental temperature remains air temperature, with the effects of air movement, long-wave radiation losses and humidity being realised through some adjustment of the observed air temperature.

2. THERMAL CONDUCTANCES

With a change of temperature of body tissues prohibited, the metabolic heat produced by the animal in unit time (H) in a thermoneutral environment may be written as:-

$$H = H_S + H_E$$

where H_S represents the rate of sensible heat loss, which is largely determined by environmental circumstance

H_E represents the rate of evaporative heat loss, which the animal has under its control.

One expression for the rate of sensible heat loss takes the form:

$$H_S = KA\ (T_B - T)$$

where A represents the skin surface area of animal

T_B represents the body temperature

K denotes the thermal conductance in cold environments (and has the dimensions heat loss per unit area per unit time per unit temperature difference). Its reciprocal is the thermal resistance to sensible heat flow from the animal.

The environmental temperature below which the heat loss by the animal exceeds the heat production (in a thermoneutral environment) may be obtained from the expression:-

$$H_S = KA\ (T_B - T) = H - H_E$$

as $$T = T_C = T_B - \frac{(H - H_W - H_E{}^1)}{AK}$$

where T_C represents the Critical Temperature

$H_E{}^1$ represents the minimum rate of heat loss by evaporation (through respiration)

H_W represents the rate at which metabolic heat is used to warm the food intake to body temperature.

Thermal resistances to heat flow (insulation) from the body core to the environment are provided by body tissues, the animals coat and the coat/air interface. These resistances to heat flow are in series and may be combined by simple addition. Noting the general reciprocal relationship between thermal resistance and thermal conductance, we may write, as a first statement:-

$$\frac{1}{K} = \frac{1}{C_T} + \frac{1}{C_F} + \frac{1}{C_A}$$

where C_T represents the thermal conductance of body tissues

C_F represents the thermal conductance of the coat or fur

C_A represents the thermal conductance of the coat/air interface.

However, the thermal resistance (insulation) by the body tissues involves the total heat produced, whilst the thermal resistances of the coat and coat/air interface involve only the sensible heat evolved. Continuity of heat flow through the body tissue, the coat and the coat/air interface in sequence requires that the resistance of the body tissues should be increased in the ratio of the total heat available to the sensible heat loss and we have:-

$$\frac{1}{K} = \frac{H}{H - H_W - H_E{}^1}\ \frac{1}{C_T} + \frac{1}{C_F} + \frac{1}{C_A}$$

The resistance to heat flow of the coat/air interface may be regarded as consisting of 2 resistances operating simultaneously and in parallel - the

resistance to convective heat loss and the resistance to long-wave radiation loss. These resistances are combined just as other resistances in parallel are combined; the reciprocals of thermal resistances r_1 and r_2 operating in parallel can be added to give the reciprocal of the total resistance, R, to heat flow.

And we have:-

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2}$$

In the present situation we may write:-

$$C_A = C_C + C_R$$

where C_A represents the thermal conductance of the coat/air

C_C represents the component of this thermal conductance to be associated with conventive heat flow

C_R represents the component of this thermal conductance to be associated with radiative heat flow.

3. THE RESISTANCE TO HEAT FLOW OF THE COAT/AIR INTERFACE

3.1. RADIATIVE EFFECTS

We may see from the expression:-

$$H_S = KA\ (T_B - T)$$

that if in a series of calorimetric studies the body temperature (T_B) of the animal remains constant, then the thermal conductance (K) is simply the slope of the line relating rate of sensible heat loss (H_S) to the environmental temperature (T).

In the calorimeter situation, with nominally still air and with wall surfaces temperatures very close ambient air temperatures, any change in the conductance (K) over a range of air temperatures can be attributed to the change in radiation demand on the animal, since all other factors remain constant.

From data provided in Blaxter (1962) we note the observed sensible heat loss from steers (with normal coats) over the ranges stated below are:-

at 20° to 10°C	400 KCal/M^2/day
0° to -10°C	500 KCal/M^2/day

At the mid point of these temperature ranges, thermal conductances (K) are taken to be:-

at 15°C	40 KCal/M^2/day/deg C
at -5°C	50 KCal/M^2/day/deg C

Identifying different environmental temperatures in the calorimeter by the suffices 1 and 2 we may write:-

$$\frac{1}{K_1} = \frac{1}{C_{T1}} + \frac{1}{C_{F1}} + \frac{1}{C_{A1}}$$

$$\frac{1}{K_2} = \frac{1}{C_{T2}} + \frac{1}{C_{F2}} + \frac{1}{C_{A2}}$$

but $C_{T1} = C_{T2}$

and $C_{F1} = C_{F2}$

in the situation under discussion.

In the present example, the decrease in the total thermal resistance to sensible heat flow due to a change in the thermal resistance to ... of the coat/air interface (and which arises from a 20°C fall in the radiative temperature of the environment) is given, numerically, by:-

$$\frac{1}{K_2} - \frac{1}{K_1} = \frac{1}{50} - \frac{1}{40} = \frac{-1}{200} \quad \text{units}$$

The corresponding increase in thermal conductance of the coat/air interface associated with this 20°C fall in radiative temperature of the environment is 200 KCal/M^2/day/deg C. By proportion, the increase to be associated with a 1°C fall in radiative temperature is 10 KCal/M^2/day/deg C.

In the calorimeter, air and wall temperatures are equated, and for this situation we write:-

$$C_A = C_C + C_R$$

In the field, the radiative temperature of the environment will in general differ from the air temperature and for this situation it is suggested that we may write:-

$$C_A = C_C + C_R + 10\ (T_A - T_R) \quad \text{KCal/M}^2\text{/day/deg C}$$

Where T_A and T_R represent the air and radiative temperatures of the environment respectively. Observations suggest C_R to be of the order 80 KCal/M^2/day/deg C. To make use of the above expression requires that we make some estimate of the departure of the radiative temperature from the air temperature. Basically our interest must be in the night time, cooling situation where there is no incoming shortwave radiation to counterbalance, or dominate, the outgoing long wave radiation loss.

This long wave radiation loss of the animal is always a net loss, compounded from the radiative output (which for our purposes is simply a function of surface temperature and is approximately constant) and the long wave radiation from the atmosphere.

With clear skies the variation in long wave absorption and re-radiation by the atmosphere is almost entirely a function of the water vapour and carbon dioxide present. Many expressions of a somewhat empirical nature are available to calculate the downward long wave radiation. We simply draw attention to one used by Penman (1948) which includes the effect of fractional cloudiness, and which makes use of the empirical dependence (found by Brunt 1932) of net long wave losses at the ground on vapour pressure at observing screen height. This has the form:

$$H_R = \sigma T_A^4 (0.56 - 0.09\ e^{\frac{1}{2}})\ (1 - 0.9c)$$

where H_R represents the net long wave radiation loss of the ground surface.

6 represents the Stefan-Boltzmann constant

e represents the vapour pressure (mm of mercury) at screen height

c represents the fractional cloudiness on a scale 0 to 10.

The result of such calculations is to suggest that with low cloud and an air temperature of $0^{\circ}C$, the radiant temperature at the zenith may be only $1^{\circ}C$ below the air temperature. With a clear sky and a very dry atmosphere, then the radiant temperature could be $20^{\circ}C$ lower than the air temperature. Such a temperature difference would be extreme in temperate climates and for the UK a more reasonable range of differences between air and radiant temperatures might be 0 to $5^{\circ}C$. Noting the dependence of the net long wave radiation loss on (c) the partial cloudiness (currently reported in Okta's) the following relation between cloud amount and the difference between air and radiant temperatures is suggested:-

Cloud Amount	8/8	7/8	6/8	5/8	4/8	3/8	2/8	1/8	0
(T_A-T_R)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0 deg C

3.2. FORCED CONVECTION EFFECTS

The problems involved in treating analytically the increasing heat loss from animals as air movement increases have been outlined in Ag Mem 473 and earlier papers. The animals have shapes which, after all, are complex, and under cold stress, their surface temperature may vary significantly from one part to another.

Observation suggests that the multiplying factor for the increase in C_A the thermal conductance of the coat/air interface, as forced air movement increases forms V_1 to V_2 m/s, is of the order $(V_2/V_1)^{0.5}$

The observed multiplying factor for the increase in C_C, the thermal conductance of simple cylinder, as forced air movement increase from V_1 to V_2 m/s is of the order $(V_2/V_1)^{0.6}$.

To reconcile the changes in C_A with wind speed, in environments in which C_R remains constant, requires, in the animal situation, that the multiplying factor for C_C should be of the order $(V_2/V_1)^{0.7}$. The partition calorimetry of Blaxter (1962) suggests a base line for C_C of 87 K cal/M^2/day/deg C, for the steer under still air, ie free convective conditions, and to which an air velocity of 0.5 m/s is attributed here.

A complete expression for C_A for steers in an environment of V m/s and in which, because partial cloudiness at night, T_R differs from A is given by:-

$$C_A = 87\ (V/0.5)^{0.7} + 80 + 10\ (T_A-T_R) \quad \text{K cal/m}^2\text{/day/deg C}$$

4. THE RESISTANCE TO HEAT FLOW OF THE COAT

For the dairy cross fattening steer, which has a relatively short coat compared for example with the possible fleece thickness of the sheep, calculations suggest we may neglect the difference between the measured and effective thickness of the coat; that is we neglect the increase in surface area available for sensible heat flow at the coat/air interface over that available at the body of the animal.

4.1. COAT THICKNESS

As long as the coat thickness is measured under thermoneutral conditions, then the simple linear increase in thermal resistance with thickness would seem to apply.

Blaxter (1965) suggests the thermal resistance of the coat for steers in still air to be 0.46 units/mm equivalent to a conductance C_F of 2.2 Kcal/m^2/day/deg C/mm^{-1}.

Under cold stress, and with pilo erection of the coat, a lower value 0.33 units/mm of the thermal resistance of the coat in still air is found. The more open nature of the coat at this time, means that there is a more effective heat transfer through it by convection currents. The thermal conductance C_F increases to a value of 3.0 K cal/m2/day/deg C/mm^{-1}.

4.2. THE EFFECT OF WIND

Low air speeds, up to 1.0 m/s, have the effect of flattening the coat. The effect is to reduce the thermal insulation since less air will be held in the coat interstices. The suggested value of the thermal resistance now is 0.40 units/mm (Blaxter 1965), equivalent to a thermal conductance C_F of 2.5 K cal/m^2/day/deg C/mm^{-1}.

At wind speeds greater than 1.0 m/s, the effect now of the wind is not simply to flatten the coat, but to spread and open it, particularly in gusts. This must obviously decrease the effective thermal resistance of the coat. There is not a great deal of experimental evidence on this effect and for want of further information, it is suggested that one might apply the power low response of the coat/air interface to this wind effect also.

Noting that the 'units' of thermal resistance (insulation) quoted throughout are deg C x 10^{-3}/K cal/m^2/day, the relation between coat thickness, wind speed and thermal resistance of the coat are taken to be as follows:-

WIND SPEED	COAT INSULATION = $1/C_F$	
	COAT NORMAL	COAT ERECTED
Still air	$\frac{0.46 \times t}{1000}$	$\frac{0.33 \times t}{1000}$
0.5 to 1.0 m/s	$\frac{0.40 \times t}{1000}$	$\frac{0.33 \times t}{1000} \left(\frac{0.5}{1.0}\right)^{0.7}$
> 1.0 m/s	$\frac{0.40 \times t}{1000} \left(\frac{1.0}{V}\right)^{0.7}$	$\frac{0.33 \times t}{1000} \left(\frac{0.5}{V}\right)^{0.7}$

where t = coat thickness in mm
V = wind speed in m/s

For our purposes we will assume that an erected coat will have twice the thickness of the normal coat.

5. BODY TISSUE

The thermal insulation of the body tissue of steers, when measured in the cold, with skin blood vessels restricted, is quoted by Blaxter 1962 as 6.7 units (equivalent to a thermal conductance of 150 Kcal/m^2/day/deg C). Such a figure represents the minimal thermal conductance of the body. Equally a figure may be quoted for the maximal amount of heat that can be transferred to the skin surface at the other environmental extreme when the blood vessels of the skin are dilated and blood flow is maximal.

Under thermoneutral conditions, Blaxter (1965) suggest a value for the thermal resistance of tissue of the adults of most species as 6.0 units (equivalent to 166 Kcal/M^2/day/deg C).

6. CRITICAL TEMPERATURES

We have from Section 2 the basic expressions:-

$$T_C = T_B - \frac{(H-H_W-H^1_E)}{K}$$

and $$\frac{1}{K} = \frac{H}{H-H_W-H^1_E}\left(\frac{1}{C_T} + \frac{1}{C_F} + \frac{1}{C_A}\right)$$

Where numerical values of heat production are now quoted per unit area (M^2) of body surface.

The following numerical values are suggested as appropriate to steers, bearing in mind our interest in cold stress:-

$T = 39.5^{\circ}C$

H (at maintenance) = 2000 Kcal/m^2/day

H (at 500g daily gain) = 2400 Kcal/m^2/day

H_W = 80 Kcal/m^2/day

H^1_E = 300 Kcal/m^2/day

The expression for T_C now reduce to:

AT MAINTENANCE

$$T_C = T_B - 1620/K$$

$$I/K = \frac{2000}{1620}\left(\frac{1}{C_T} + \frac{1}{C_F} + \frac{1}{C_A}\right)$$

AT DAILY GAIN OF 500 g

$$T_C = T_B - 2020/K$$

$$I/K = \frac{2400}{2020}\left(\frac{1}{C_T} + \frac{1}{C_F} + \frac{1}{C_A}\right)$$

6.1. FOR THE STORE ANIMAL, in still air, with an erected coat of 20 mm we have:-

$$\frac{1}{C_T} = \frac{6.7}{1000} \; ; \; \frac{1}{C_F} = \frac{0.33 \times 20}{1000} \; ; \; \frac{1}{C_A} = \frac{6.0}{1000}$$

$$I/K = \frac{20.85}{1000}$$

$$T_C = 8^{\circ}C$$

For the fattening animal under these environmental conditions we found:

$$T_C = -2^{\circ}C$$

6.2. FOR THE STORE ANIMAL, in an air movement of 1.0 m/s with an erected coat of 20 mm we have:-

$$\frac{1}{C_T} = \frac{6.7}{1000} \; ; \; \frac{1}{C_F} = \frac{0.33 \times 20}{1000} \frac{(0.5)^{0.7}}{(1.0)} \; ; \; \frac{1}{C_A} = \frac{1000}{\left[87 \frac{(1.0)^{0.7}}{(0.5)} + 80\right]} \times 1000$$

$$I/K = \frac{16.85}{1000}$$

$$T_C = 12.0^{\circ}C$$

For the fattening animal under these environmental conditions we found:

$$T_C = 6^{\circ}C$$

6.3. FOR THE STORE ANIMAL, in an air movement of 5.0 m/s with an erected coat of 20 mm we have:-

$$\frac{1}{C_T} = \frac{6.7}{1000}$$

$$\frac{1}{C_F} = \frac{0.33 \times 20}{1000} \frac{(0.5)^{0.7}}{(5.0)} = \frac{0.33 \times 20}{1000 \times 5.01} = \frac{1.32}{1000}$$

$$\frac{1}{C_A} = \frac{1000}{1000 \left[87 \frac{(5.0)^{0.7}}{(0.5)} + 80\right]} = \frac{1000}{1000 \left[87 (5.01) + 80\right]} = \frac{1.94}{1000}$$

$$I/K = \frac{11.5}{1000}$$

$$T_C = 20^{\circ}C$$

For the fattening animal under these environmental conditions we find:

$$T_C = 17^{\circ}C$$

7. THE SENSITIVITY OF THE CRITICAL TEMPERATURE CALCULATIONS

The prime environmental determinant of Critical Temperature that we have considered is wind speed. It is of interest to examine the sensitivity of the Critical Temperature estimates to the numerical value assigned to the multipliers of thermal conductances that introduce wind effects. We repeat the calculations of paragraphs 6.1 to 6.3 (and for the further wind speed of 2.5 m/s) when the index of 0.7 (for the conductance multipliers) is changed to 0.6 and 0.5.

The results are shown in the following table:-

TABLE CRITICAL TEMPERATURES UNDER VARIOUS MULTIPLIERS FOR WIND EFFECTS

Wind Speed	Index of conductance multiplier		0.7	0.6	0.5
	'Still Air'	S	8.0°C	8.0°C	8.0°C
		F	-2.0°	-2.0°	-2.0
	1.0 m/s	S	12.0°C	11.5°C	10.5°C
		F	6.0°	5.0°	4.0°
	2.5 m/s	S	13.9°C	13.0°C	11.7°C
		F	8.2°	7.0°	5.4°
	5.0 m/s	S	20.0°C	19.7°C	18.0°C
		F	17.0°	15.4°	13.5

S = Store animal (H = 2000 KCal/m^2/day)
F = Fattening animal (H = 2400 KCal/m^2/day

It would seem that the consequences of increase of wind speed (ie increasing heat loss and a higher Critical Temperature) are of greater importance than the value adopted for the index of the wind multiplier.

8. DISCUSSION

One inference, that may be drawn from the work of McCarrick and Dermnan (1972) on the wintering of young beef cattle in Central Eire, is that the effects of rainfall on liveweight gain in this area are minimal.

Ag Mem 473 shows that air temperature, and wind speed are the primary environmental variables of interest in this respect.

This paper suggests how one may calculate a modified Critical Temperature appropriate to a range of field situations.

We may comment that the 'still air' conditions appropriate to the calorimeter studies will seldom apply 'in the field' and that a minimum air movement of 1.0 m/s might be adopted. Except near the coast, (and on exposed high ground) an average wind speed of less than 5.0 m/s will be found over most parts of Great Britain.

Given the ability of animals to seek shelter and to provide some mutual protection from the elements, a mean air movement for the group of animals on the farm might be taken as nearer 2.5 than 5.0 m/s.

A following memorandum (Ag Mem 527) shows how the extent and duration of exposure to air temperatures below any nominated Critical (air) Temperature may be readily calculated.

A further Memorandum (Ag Mem 528) is intended to show the economic consequences of exposure to environmental temperatures below the Critical Temperature.

Meteorological Office
Cambridge

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